Future of Commercial Payloads

Canaveral Council of Technical Societies

CCTS

SESSION IC

REUSABLE LAUNCH VEHICLE CERTIFICATION

Edgar Zapata
National Aeronautics and Space Administration
Kennedy Space Center
February 16, 1996

Abstract

This paper will discuss the flight certification of the next generation Reusable Launch Vehicle (RLV). It will define certification as currently understood, as it will be required in the future, the difference between these two, and what this difference means for the next generation systems design.

Together, NASA and industry have been tasked with demonstrating technologies focused on a reusable single stage to orbit (SSTO) vehicle which will dramatically reduce the costs of achieving low earth orbit. This vision of routine and affordable access to space, if achieved, is driven toward bringing the benefits of space to humanity through a quantum leap in accessibility by means of drastically reduced vehicle turnaround times and recurring flight costs. The approach to certification will be key to the success or failure of this endeavor. Previous and current space vehicle efforts are familiar with the term “certification”. However, the express goals of the RLV program, by necessity, will alter the current definition and mindset toward “certification”.

This paper will focus principally on the certification process from two perspectives. The first is the NASA Shuttle operation and it’s approach to certification. This is chosen for being the only current space vehicle with partial reusability. It is, therefore, a starting point. The second perspective is the virtual target for operation of the next generation RLV. This vehicle has yet to be defined although many concepts, technologies and approaches are being worked by NASA and industry. It is precisely the approach to certification that will shape the future of this program and the eventual approach to the design. This approach, in turn, will define the resulting configuration.

In the process of defining certification for the RLV previous efforts in this area will be reviewed. The subjects of reliability, vehicle health management or “smart systems”, affordability and supportability will be discussed in relation to the issue of certification. Also, the relationship of certification to launching off a range versus flying off an operational site will be reviewed. Other applicable subjects such as the methods of the U.S. Federal Aviation Administration will also be discussed. Current RLV concepts and program material relevant to technology pursuits and goals will also be reviewed with relation to the subject of certification.

Certification - Definition

The use of the term “certification” as focused on here is that process which assures a design is capable of safely carrying out it’s intended purpose. For a Reusable Launch Vehicle certification the goal is to assure flight worthiness of a system. It is also intended the certification be for “continued” flightworthiness since reusability is a principal characteristic of the system.

It is not the intent hereto emphasize the term certification in reference to processes that assure the readiness for use of a particular vehicle or launch system. Neither is the intent here to associate the term with the processes by which a particular vehicle is maintained flightworthy. For this, the terms processing or maintenance are more appropriately used as separate from certification.

<u>Current NASA Shuttle Certification Processes - Two Types</u>

In any discussion of Shuttle certification a distinction must be made between that certification which is a part of the research, design and development process through implementation versus that certification which occurs continually such as from flight to flight.

- The first type of certification involves development of systems to a degree that subsequent assemblies can be manufactured and operated without having to undergo the same degree of test or scrutiny. It is also referred to often as “qualification” or “qual test”.

- The second type of certification involves processes which assure a particular, actual assembly (part, component, subassembly, line replaceable unit or LRU, system or whole vehicle and ground system) is ready for operational use or flight. This last may also be called “processing” (or maintenance) leading to certification though many sub-categories of processes may be identified here for a system such as the Space Shuttle.

A current example of the first type of certification is the Space Shuttle Main Engine (SSME) Alternate Turbopump Development (ATD) program. Turbopumps area major part of the turnaround work on the SSME’s. The Shuttle main engines in particular, propulsion in general, is one of the main drivers of Shuttle recurring costs whether strictly at Kennedy Space Center (KSC) or through the associated infrastructure (people and facilities) that exist elsewhere around the country such as in these development efforts.

A related example of the second type of certification is the tracking and application of allowable life limits to processing a particular serial number engine. This determines what stays versus what is removed and replaced during engine refurbishment for example.

These two uses of the term “certification” are very interrelated. One* tie between the two is the fleet leader program. Fleet leader components are set aside for the express purpose of being tested well beyond what would be acceptable for flight. Their purpose is to provide experience and knowledge into allowable life limits for components. Low and high cycle fatigue limits, analogous to starts and seconds (all similar to aircraft terminology), are determined by previous histories which include fleet leader components. For example, [18] when extensive fleet hot-fire exposure data are available and there are no failures or major material review disposition (MRD) history, the life limit may be 25 percent of fleet leader. Under some criterion (requiring periodic inspection) this may be 50 percent of the representative fleet leader or the failed unit if one has occurred.

The above values of 25 and 50% are the result of applying factors of safety of 4 and 2 to the components. This would seem to indicate a high degree of safety and margin in the hardware. However, the ATD program was begun precisely to address criticality issues first, and second to eliminate removal and replacement of the Rocketdyne Turbopumps every flight. *For many components safety factors of 2 or 4 can and do equal only a few uses given fleet leader experience that shows short useful lives.*

---

* Other methods used include analysis to determine life limits and assure reliability.

If a fleet leader builds an experience base that, when factors of 2 are applied, results in operating limits that are low, the certification of systems built from those components has that much greater difficulty in realizing any goal of reusability with little or no maintenance between uses. For example, a Deviation Approval Request (DAR) for a turnaround duct may establish a life limit of 5 starts where the original requirement was for 60. Only by continuing to accumulate time on the fleet leaders (or development articles in this case) and having no failures can the limit be raised eventually toward the original goal.

Returning to the distinctions about the types of certification, it becomes clear then that the second type of certification, certification of particular hardware, might more appropriately be called "Verification of Flight Readiness" or "worthiness". As the useful life of systems diminishes and the resource intensiveness of turnarounds increases, the "verification" then becomes equated with "certification." This previous type of certification is causally related to the first type of certification (a truer use of the term), certification of designs so that subsequent assemblies need not receive the same degree of scrutiny (resources) while still assuring readiness for operation, safety during use, and the capability to carry out the intended purpose.

The ATD LOX turbopump, by virtue of it's certification process, will allow greater reuse without any changes in safety factors. Having accumulated run times on units equal to over 40 flights or 20,000 seconds, the pump is then safely used up to 10 times (using the factor of 4) without any scheduled maintenance. This assumes among** other things no major failures during this testing. This is not to say the road to reusability is entirely clear.

** Such as the ability to control production processes so as to have consistent, repeatable results (subsequent manufactured units).

<u>Alternate Turbopump Development -An Example of Certification of the First Type</u>

The establishment of longer life limits through extensive testing is a focus of the Pratt & Whitney ATD program. This basic philosophy should allow the LOX turbopumps on the SSME's to be left on for 10 flights without a need for removal as exists on the Rocketdyne design. However, the new turbopumps, set to fly on STS-70, have had their share of problems. The first flight P&W High Pressure Oxidizer Turbopump (HPOTP) was shipped to KSC installed on an engine but nonetheless had to be removed and replaced later on. The new preburner boost pump impeller end balancer material was deemed inadequate. * The replacement too had it's problems, in this case an inlet guide vane crack issue. This will require inspections, not planned at all, after every flight for this particular S/N unit only. This is not to say the approach or basic philosophy is flawed. Actually, the ATD will likely enhance reusability (possibly saving up to a weeks worth of work per SSME turnaround). The basic approach is what will likely be required in the future - only more so.

Consider the implications for a program such as RLV. The ATD program has so far spent $1.2 Billion on one turbopump. For the RLV, 10 flights is only the beginning. Not only will components have to be reusable to degrees not yet seen, they will have to take the additional step that no inspections be required. The R+D effort required for the realization of this goal will likely require, even with much

* The impeller is balanced in a process that basically removes material and then achieves balance by adding set screws that are staked to preclude backing out or loosening. These set screws were made of tantalum. The material is dense so as to require few for balancing. Cracking (heads cracked through on the screws) was discovered to be a problem leading to loosening. The decision was made to switch to a stainless steel. This will mean more maybe required for balancing (a less dense material). Notably, the particular pump passed inspection but, given the experience on other units in work the decision was made to remove and replace the pump.

improved cost control and management techniques, far more than the currently foreseen finding for RLV. *"Aircraft type operations" will require true, extended reusability built into a design as a result of certification of the first type, rigorous development of systems to a degree that subsequent assemblies need not require the same degree of test or scrutiny, and the associated baggage - manpower and infrastructure.*

Aircraft Type Operations. the FAA and Shuttle - a Comparison of Certifications of the First Type

Government rules and regulations are imposed on airplane manufacturers and operators to guarantee the general public a certain level of safety. This is done through the Federal Aviation Administration (FAA). The origins here trace back to 1926 and the Air Commerce Act which authorized the first significant federal regulation of civil aviation. Duties given to the Secretary of Commerce included fostering air commerce, establishing airways, investigating accidents and certifying aircraft. The new Aeronautics Branch that was formed eventually led to the formation of the FAA in 1958. By 1970 responsibilities also included setting airport safety standards and certificating those facilities as well.

It maybe argued that using aircraft type analogies to space operations avoids obvious differences such as the extremely demanding operational environments of a launch or the on-orbit and re-entry environment. However, it is relevant here to consider approaches (not results) used in the aircraft arena that reflect on how to one day make launch systems that do have "aircraft like operations". Aircraft designers and launch system designers must each design for certain environments. The question is not whether the environments are similar but whether the approach used in one situation to meet requirements is applicable to the other. For an SSME, as an example, the major contributor to life limitations is the internal thermal environment. [1]1 It is estimated 70°/0 of the problems encountered on a high-pressure fuel turbopump (HPFTP) are thermally induced. Transients* * such as the startup process represent the most severe environment. The startup temperature transient is especially a major element in limiting turbine life. The thermal shock to the turbine airfoils during preburner startup may be imagined by visualizing a surface that wants to expand but a core that is cool and only catches up later. This thermal delta occurs quickly but with enough of a difference to cause thermal stresses and hence crack propagation concerns. Again, aircraft do not see such environments, but some approaches used in the aircraft world to meet their environments can shed light on how to overcome launch system environments. If a goal of any reusable launch vehicle is to have operations like aircraft it is certainly relevant to review how aircraft got where they are.

Advisory Circulars are used by the FM as non mandatory guides to meeting actual requirements or Federal Aviation Regulations (FAR's). Start-stop cyclic stresses or low cycle fatigue (LCF) are addressed in the [8]following:

> "By a procedure approved by the FAA operating limitations must be established which specify the maximum allowable number of start-stop stress cycles for each rotor structural part (such as discs, spacers, hubs, and

** The 1850R temperatures in this transient are addressed in the new Pratt & Whitney ATD by the use of hollow airfoils. Tactics such as decreasing operating temperatures (using either fuel rich or oxidizer rich cycles) do not address this start transient, LCF problem but do address high cycle fatigue. Pressure transients also contribute to the LCF problem. Notably, aircraft turbine engines operate up to 2160R uncooled. Current aircraft turbine inlet temperatures are as high as 3260R and are being pushed toward 4600R, the stochiometric limit of JP4 fuel. However, the ramp up to these temperatures is slow compared to the SSME startup.

shafts of the compressors and turbines), the failure of which could produce a hazard to the aircraft. A start-stop stress cycle consists of a flight cycle profile or an equivalent representation of engine usage. It includes starting the engine, accelerating to maximum rated power or thrust, decelerating, and stopping. For each cycle the rotor structural parts must reach stabilized temperature during engine operation at a maximum rate power or thrust and after engine shutdown, unless it is shown that the parts undergo the same stress range without temperature stabilization"

For materials the suitability and durability must "Be established on the basis of experience or test".

The actual number of cycles will be derived in many cases from pre-approved procedures already on file with the FAA for establishing initial LCF lives. The most severe mission cycle will be used in these determinations.

Tests that will form a part of the high-cycle fatigue (HCF) profile for turbine aircraft engines include 150 hour endurance tests accumulated by running 6-hour test sequences 25 times. If major repairs or the frequency of service is excessive during these tests then the engine will be subjected to further tests. Other tests will include vibration, calibration, detonation and operation tests. In conducting these [6]block tests separate engines of identical design and construction may be used for each of the various tests.

A current example here is the certification of the Pratt & Whitney PW4084 powerplant for the new Boeing 777. Tests included 3000 simulated (off aircraft) flight cycles with no major component failures and the ability to demonstrate maximum continuous thrust for 3 hours in repeated testing. Flight tests will further include another 1000 cycles. Again, the emphasis is "no major component failures" so as to demonstrate high life limits for both low and high cycle fatigue. Unique to the PW4084 case is the goal of demonstrating extended twin operations (ETOPS) or that is the ability to maintain the performance necessary for single engine flight. The focus here is to develop and demonstrate from the start the suitability for a particular type of operation such as ETOPS rather than to operations which are less demanding but more constrained. Another alternative would have been to initially certify to a less demanding operation and then allow the evolving flight experience to extend the operations envelope. This could also have also resulted in ETOPS certification eventually. By certifying for ETOPS, customer requirements for flexibility (usable on many routes) and reduced operations costs (twin jets versus aircraft using more engines to allow ETOPS) are enabled from day one of delivery.

Maintaining certification once it is achieved will be done through maintenance according to certification maintenance requirements (CMR's). CMR's should not be confused with maintenance requirements arising from certification nor with other scheduled maintenance requirements. For a Boeing 767 the [3]"CMR tasks are identified whenever system probabilities and failure effects are not expected to fall within an acceptable range without a periodic maintenance requirement". CMR's or any changes to CMR's are approved exclusively by FAA engineering. For a 767 most of the CMR frequencies are in the range of thousands of hours of flight time. Prior to these times other requirements that may have been scheduled may have covered the items. These frequencies also list in the thousands of cycles and hours of usage.

For comparison, a review of a high pressure fuel turbopump (HPFTP) on a Shuttle SSME will show a life* usage of 8 starts and 2767 seconds. This does not represent usage since the last check. It does not include repair and refurbishment. Major work may have been performed on the assembly during this time. Failures may also have occurred. The usage numbers are only useful to a next order assembly such as the housing [12]. Fleet leader numbers may be 69 starts and 25861 seconds for a HPFTP. Again, the same caveats apply. Work on the Rocketdyne Shuttle HPOTP's is done after every flight. Removal from the engine is driven by recurring problems with a tip seal retainer. This retainer uses set screws, staked in place, to hold it in. The backing out of these screws and a history of machining tolerance problems on the tip seal itself drives the removal every flight on the HPOTP's. Unlike other work which is also required every flight, this particular item, an inspection, can not be done with the pumps installed on the engines. Following the fulfillment of requirements such as these, a particular serial number set of pumps maybe certified for a particular Shuttle flight. However, these will have limited relevance to other pumps and other certification processes. It is the fleet leaders that will bear greatest relevance in certifying not only individual similar items but also the design in general. Again, however, short fleet leader lives will in turn create short actual lives for components to be used.

This is not to say that life limits comparable to the aircraft analogy apply to the case of the launch system. The need and ability for loitering capability in aircraft has as yet no equal in a comparison to a launch vehicle during ascent. The relevance is to methodology used in one case such as aircraft as a reflection on the *testing for certifcation* of candidate reusable launch vehicles and systems. *The rigorous testing used for the design and subsequent certfication of aircraft systems for high life limits and usage results in designs capable of extended reuse with no major failures between uses.* This reflects on what will be required to design and certify a reusable launch vehicle for extended reuse with no major failures between uses.

Interestingly, before the FAA was formed, the certification of airline pilots and airplanes was done by Underwriters Laboratories (UL) which is today the world's largest independent certifier of product safety. While safety and reliability or reusability issues do not always overlap, they have in common a need for systems to demonstrate the ability to operate as planned under the most severe operating and environmental conditions. UL is well known for testing products by turning them on and off hundreds of thousands, perhaps millions, of times or perhaps turning them on and leaving them that way for ridiculously extended time periods. Design and destruction leads to the familiar UL symbol on multitudes of products which are safe and certified. It maybe said they are "free of range constraints".

Final Summary - What Will be Required for RLV Certification

The RLV technology program goals are extremely ambitious. The basic goal is to demonstrate technologies leading to a reusable launch vehicle that will be affordable and provide routine access to space. Low cost and high availability will only be combined through a reduction on single vehicle turnaround times.

True certification is development of systems to a degree that subsequent assemblies can be manufactured and operated without having to undergo the same degree of test or scrutiny. Having reviewed aircraft methodologies it can be shown that the rigorous testing used for the

* The actual usefulness of tracking regardless of the degree of repair and refurbishment is as an indication of life limits for some internal components which are used over and over with only inspections. A sheet metal problem can, for example, be better understood by comparing a unit set to fly against higher life units.

design and subsequent certification of aircraft systems for high life limits and usage results in designs capable of extended reuse with no major failures between uses. This approach is one key to reducing turnaround times and achieving RLV goals.

For a reusable launch system to one day sever it's ties to a range, and transition to a truly operational site, or no longer require explosive charges, the reliability of the system will first have to be demonstrated. Rigorous certification processes for components and subsystems will increase reliability and the likelihood of demonstrating no need for a range. A key to establishing a high demonstrated reliability for the whole launch system, however, will be to also reduce fictional complexity of the launch system. Reducing functional complexity means both "fewer" and for what's left, "more integrated. " A reduction in functional complexity will also reduce criticality complexity.

Complexity driving one way, toward greater mission reliability, but opposingly, toward less support reliability, ceases to be true. A reusable launch system focused on simplicity has the greatest likelihood of achieving the combination of demonstrating high mission reliability aimed toward freeing itself from the "range" as well as doing so affordably.

An advanced, health management system (HMS) focused on ground turnaround will be required for any RLV aimed at one time only certification and the twin goals of affordability and high availability. This additional system should be evolved from turnaround operational concerns versus current systems focused on ascent or on orbit operations only.

An HMS will be a necessary complement to rigorous certification processes at all system levels, reductions in complexity, and demonstration of reliability. This is key to *true certification, development of systems to a degree that subsequent assemblies can be manufactured and operated without having to undergo the same degree of test or scrutiny.*

In closing, although this paper is not intended to address issues of cost in relation to certification, it is highly probable that the foreseen finding for reusable launch system technologies is inadequate assuming a certification approach as previously reviewed which is consistent with achieving the long term goals of affordable and highly available transportation to space. The term "quantum leap" is often used in the program to refer to what is technologically required to dramatically reduce the cost of space transportation. This would seem to imply that whereas once there was continuity of development all of a sudden there will be a discontinuity, a new state with no traceable connection between it and what came before. This is unlikely. This is not to say affordable and highly available space transportation can not be achieved. However, rigorous certification at all system levels, reductions in complexity, demonstrated reliability and advanced health management systems will be required. This will involve an appreciable investment in the future. This will create the path connecting where we are to where we want to go.

Internet Note

Due to space limitations it is not possible here to give due credit to the subject at hand. A more extensive and complete version of this paper is available via the Internet under the same subject name at the following website address:

http://calvin.ksc.nasa.gov:lO8O/nexgen/rlvhp.htm

References

1. Advisory Group for Aerospace Research and Development, AGARD, Smart Structures for Aircraft and Spacecraft, AGARD Conference Proceedings 531 Lindau, Germany, October 1992.

2. Aerospace Engineering, Condition Monitoring and Diagnostics, SAE International, January/February 1995.

3. Boeing Company, Boeing 767 Maintenance Planning Data Volume 2

4. Boiler, Chr. and Dilger, R., In-Flight Aircraft Structure Health Monitoring Based on Smart Structures Technology, AGARD Conference Proceedings 531, Section 17, October 1992.

5. Department of Defense, Logistics Support Analysis. MIL-STD-1388-lA , 11 April, 1983

6. Federal Aviation Administration, U.S. Dept. of Transportation, Aircraft Engine Type Certification Handbook, Advisory Circular AC 33-2B , June 30, 1994.

7. Federal Aviation Administration, U.S. Dept. of Transportation, Certification Procedures for Products and Parts, Special Federal Aviation Regulations, Subchapter C - Aircraft, Part 21.

8. Federal Aviation Administration, U.S. Dept. of Transportation, Airworthiness Standards: Aircraft Engines, Special Federation Aviation Regulations, Subchapter C - Aircraft, Part 33.

9. Feynman, R. P., “Personal Observations on the Reliability of the Shuttle,” Report by the Presidential Commission on the Space Shuttle Challenger Accident, Appendix F, 1986.

10. GelI-Mann, Murray., The Quark and the Jaguar. Adventures in the Simple and the Complex, Princeton University Press, 1994.

11. Goracke, B. David, Levack, Daniel J. H., Margin Considerations in SSTO 02/H2 Engines, AIAA 94-4676, AIAA Space Programs and Technologies Conference and Exhibit, September 27-29, 1994.

12. National Aeronautics and Space Administration, Endeavour. STS-68 Delta SSME Project, SSME Flight Readiness Review, 21 September 1994.

13. National Aeronautics and Space Administration / Industry Operations Synergy Team, Operations Concept Vision and Operability Criteria Document, November 1994.

14. National Aeronautics and Space Administration, Marshall Space Flight Center, RLV Concept Study Team Review, October 1994.

15. National Aeronautics and Space Administration, Johnson Space Center, Space Shuttle Requirements and Procedures for Certification of Flight Readiness (NSTS 08117), February 21, 1995.

16. National Aeronautics and Space Administration, SSME Accident/ Incident Report SSC Test 904-044, Rockwell International, 23 June 1994.

17. National Aeronautics and Space Administration, Subsystem Certification Plan, Main Propulsion, Rockwell International, November 1977.

18. Rockwell International Corporation, Rocketdyne Division, SSME Component Allowable Life and Hardware Tracking Program Requirements, Specification - RLO0532, Rockwell International, February 1994.

19. SAE International RMS Committee (G-11), Reliability, Maintainability. and Supportability Guidebook. 2nd Edition, Society of Automotive Engineers, Inc., 1992.

20. Schmidt, W. and Boiler, Chr.,Smart Structures, A Technology For Next Generation Aircraft, AGARD Conference Proceedings 531, Section 1, October 1992.

21. Smiljanic, Ray R., Definitions, Models and Methods for Supportability Analyses, McDonnell Douglas Aerospace (MDA), 28 June 1994.

22. U.S. Statistical Abstract, U.S. Major and National Airline Costs, Air Transport Association of America, 1993.

Acknowledgments

Dave Spacek, NASA KSC, on the subject of Space Shuttle Main Engine Alternate Turbopump Development.

D.R. Komar, NASA KSC, on the subject of KSC Space Shuttle Main Engine verification and processing for flight.